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CHAPTER 1

HISTORICAL PERSPECTIVE OF ELECTRICAL CABLES

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1. DEVELOPMENT OF UNDERGROUND CABLES [1-1, 1-2]

In order to trace the history of underground cable systems, it is necessary to examine the early days of the telegraph. The telegraph was the first device utilizing electrical energy to become of any commercial importance and its development necessarily required the use of wires. Underground construction was advocated by the majority of the early experimenters. Experimentation with underground cables accordingly was carried on contemporaneously with the development of the apparatus for sending and receiving signals. Underground construction was planned for most of the earliest commercial lines. A number of these early installations are of considerable interest as marking steps in the development of the extensive underground power systems in operation around the world.

2. EARLY TELEGRAPH LINES

In 1812, Baron Schilling detonated a mine under the Neva River at St. Petersburg by using an electrical pulse sent through a cable insulated with strips of India rubber. This is probably the earliest use of a continuously insulated conductor on record.

One of the earliest experiments with an underground line was made by Francis Ronalds in 1816. This work was in conjunction with a system of telegraphy consisting of 500 feet of bare copper conductor drawn into glass tubes, joined together with sleeve joints and sealed with wax. The tubes were placed in a creosoted wooden trough buried in the ground. Ronalds was very enthusiastic over the success of this line, predicting that underground conductors would be widely used for electrical purposes, and outlining many of the essential characteristics of a modern distribution system.

The conductor in this case was first insulated with cotton saturated with shellac before being drawn into the tubes. Later, strips of India rubber were used. This installation had many insulation failures and was abandoned. No serious attempt was made to develop the idea commercially.

In 1837, W. R. Cooke and Charles Wheatstone laid an underground line along the railroad right-of-way between London's Euston and Camden stations for their five-wire system of telegraphy. The wires were insulated with cotton saturated in rosin and were installed in separate grooves in a piece of timber coated with pitch. This line operated satisfactorily for a short time, but a number of insulation failures due to the absorption of moisture led to its abandonment. The next year, Cooke and Wheatstone installed a line between Paddington and Drayton, but iron pipe was substituted for the timber to give better protection from moisture. Insulation failures also occurred on this line after a short time, and it was also abandoned.

In 1842, S. F. B. Morse laid a cable insulated with jute, saturated in pitch, and covered with strips of India rubber between Governor's Island and Castle Garden in New York harbor. The next year, a similar line was laid across a canal in Washington, D.C. The success of these experiments induced Morse to write to the Secretary of the Treasury that he believed "telegraphic communications on the electro-magnetic plan can with a certainty be established across the Atlantic Ocean."

In 1844, Morse obtained an appropriation from the U.S. Congress for a telegraph line between Washington and Baltimore. An underground conductor was planned and several miles were actually laid before the insulation was proved to be defective. The underground project was abandoned and an overhead line erected. The conductor was originally planned to be a #16 gage copper insulated with cotton and saturated in shellac. Four insulated wires were drawn into a close fitting lead pipe that was then passed between rollers and drawn down into close contact with the conductors. The cable was coiled on drums in 300 foot lengths and laid by means of a specially designed plow.

Thus, the first attempts at underground construction were unsuccessful, and overhead construction was necessary to assure the satisfactory performance of the lines. After the failure of Morse's line, no additional attempts were made to utilize underground construction in the United States until Thomas A. Edison's time.

Gutta-percha was introduced into Europe in 1842 by Dr. W. Montgomery, and in 1846 was adopted on the recommendation of Dr. Werner Siemens for the telegraph line that the Prussian government was installing.

Approximately 3,000 miles of such wire were laid from 1847 to 1852. Unfortunately, the perishable nature of the material was not known at the time, and no adequate means of protecting it from oxidation was provided. Insulation troubles soon began to develop and eventually became so serious that the entire installation was abandoned.

However, gutta-percha provided a very satisfactory material for insulating telegraph cables when properly protected from oxidation. It was used

extensively for both underground and submarine installations.

In 1860, vulcanized rubber was used for the first time as an insulation for wires. Unvulcanized rubber had been used on several of the very early lines in strips applied over fibrous insulation for moisture protection. This system had generally been unsatisfactory because of difficulties in closing the seam. Vulcanized rubber proved a much better insulating material, but did not become a serious competitor of gutta-percha until some years later.

3. ELECTRIC LIGHTING

While early telegraph systems were being developed, other experimenters were solving the problems connected with the commercial development of electric lighting. An electric light required a steady flow of a considerable amount of energy, and was consequently dependent upon the development of the dynamo. The first lamps were designed to utilize the electric arc that had been demonstrated by Sir Humphry Davy as early as 1810. Arc lights were brought to a high state of development by Paul Jablochhoff in 1876 and C. R. Brush in 1879. Both men developed systems for lighting streets by arc lamps connected in series supplied from a single generating station

Lighting by incandescence was principally the result of the work of Edison, who developed a complete system of such lighting in 1879. His lights were designed to operate in parallel instead of series as had been the case with the previously developed arc-lighting systems. This radical departure from precedent permitted the use of low voltage, and greatly simplified the distribution problems.

4. DISTRIBUTION OF ENERGY FOR LIGHTING

Edison planned his first installation for New York City, and decided that an underground system of distribution would be necessary. This took the form of a network supplied by feeders radiating from a centrally located dc-generating station to various feed points in the network. Pilot wires were taken back to the generating station from the feed points in order to give the operator an indication of voltage conditions on the system. Regulation was controlled by cutting feeders in, or out, as needed. At a later date, a battery was connected in parallel with the generator to guard against a station outage.

Gutta-percha, which had proved a satisfactory material for insulating the telegraph cables, was not suitable for the lighting feeders because of the softening of the material (a natural thermoplastic) at the relatively high operating temperature. Experience with other types of insulation had not been sufficient to provide any degree of satisfaction with their use. The development of a cable sufficiently flexible to be drawn into ducts was accordingly considered a rather remote possibility. Therefore, Edison designed a rigid, buried system consisting of copper rods insulated with a wrapping of jute. Two or three insulated rods were drawn into iron pipes and a heavy bituminous

compound was forced in around them. They were then laid in 20-foot sections and joined together with specially designed tube joints from which taps could be taken if desired. The Edison tube gave remarkably satisfactory performance for this class of low voltage service.

The low voltage and heavy current characteristics of dc distribution were limited to the area capable of being supplied from one source if the regulation was to be kept within reasonable bounds. The high first cost and heavy losses made such systems uneconomical for general distribution. Accordingly, they were developed in limited areas of high-load density such as the business districts of large cities.

In the outlying districts, ac distribution was universally employed. This type of distribution was developed largely as a result of the work, in 1882, of L. Gaulard and J. D. Gibbs, who designed a crude alternating current system using induction coils as transformers. The coils were first connected in series, but satisfactory performance could not be obtained. However, they were able to distribute electrical energy at a voltage considerably higher than that required for lighting, and to demonstrate the economics of the ac system. This system was introduced into the United States in 1885 by George Westinghouse, and served as the basis for the development of workable systems. An experimental installation went in service at Great Barrington, Massachusetts, early in 1886. The first large scale commercial installation was built in Buffalo, New York, the same year.

The early installations operated at 1,000 volts. Overhead construction was considered essential for their satisfactory performance and almost universally employed. This was also true of the street-lighting feeders, which operated at about 2,000 volts. In Washington and Chicago, overhead wires were prohibited, so a number of underground lines were installed. Many different types of insulation and methods of installation were tried with little success. Experiments with underground conductors were also carried out in Philadelphia. The 1884 enactment of a law forcing the removal of all overhead wires from the streets of New York mandated the development of a type of construction that could withstand such voltages. It was some time, however, before the high-voltage wires disappeared. In 1888, the situation was summarized in a paper before the National Electric Light Association as follows:

“No arc wires had been placed underground in either New York or Brooklyn. The experience in Washington led to the statement that no insulation could be found that would operate two years at 2,000 volts. In Chicago, all installations failed with the exception of lead covered cables which appeared to be operating successfully. In Milwaukee, three different systems had been tried and abandoned. In Detroit, a cable had been installed in Dorsett conduit, but later abandoned. In many of the larger cities, low voltage cables were operating

satisfactorily and in Pittsburgh, Denver and Springfield, Mass., some 1,000 volt circuits were in operation."

5. PAPER INSULATED CABLES [1-3]

The first important lines insulated with paper were installed by Ferranti in 1890 between Deptford and London for operation at 10,000 volts. Some of these mains were still in use at the original voltage after more than 50 years. The cables consisted of two concentric conductors insulated with wide strips of paper applied helically around the conductor and saturated with a rosin based oil. The insulated conductors were forced into a lead pipe and installed in 20 foot lengths. These mains were not flexible and were directly buried in the ground.

Soon after, cables insulated with narrow paper strips saturated in a rosin compound and covered with a lead sheath (very similar in design to those in use at the present time) were manufactured in the United States by the Norwich Wire Company. These were the first flexible paper-insulated cables, and all subsequent progress has been made through improvements in the general design.

Paper insulated cables were improved considerably with:

- (a) Introduction of the shielded design of multiple conductor cables by Martin Hochstadter in 1914. This cable is still known as Type H.
- (b) Luigi Emanuelli's demonstration that voids due to expansion and contraction could be controlled by the use of a thin oil with reservoirs. This permitted the voltages to be raised to 69 kV and higher.
- (c) The 1927 patent by H. W. Fisher and R. W. Atkinson revealed that the dielectric strength of impregnated paper-insulated cable could be greatly increased by maintaining it under pressure. This system was not used until the 1932 commercial installation of a 200 psi cable in London.

Impregnated paper became the most common form of insulation for cables used for bulk transmission and distribution of electrical power, particularly for operating voltages of 12.5 kV and above, where low dielectric loss, a low dissipation factor, and a high ionization level are important factors in determining cable life.

Impregnated paper insulation consists of multiple layers of paper tapes, each tape from 2.5 to 7.5 mils in thickness, wrapped helically around the conductor to be insulated. The total wall of paper tapes is then heated, vacuum dried, and impregnated with an insulating fluid. The quality of the impregnated paper

insulation depends not only on the properties and characteristics of the paper and impregnating fluid, but also on the mechanical application of the paper tapes over the conductor, the thoroughness of the vacuum drying, and the control of the saturating and cooling cycles during the manufacturing.

Originally, most of the paper used was made from Manila-rope fiber. This was erratic in its physical properties and not always susceptible to adequate oil penetration. Increased knowledge of the chemical treatment of the wood (in order to obtain pure cellulose by the adjustment of the fiber content and removal of lignin), the control of tear resistance, and the availability of long fiber stock resulted in the almost universal use of wood pulp paper in cables after 1900.

The impregnating compound was changed from a rosin-based compound to a pure mineral oil circa 1925, or oil blended to obtain higher viscosity, until polybutene replaced oil circa 1983.

Paper insulated, lead-covered cables were the predominant primary cables of all the large, metropolitan distribution systems in the United States, and the rest of the world, throughout the twentieth century. Their reliability was excellent. It was, however, necessary to have a high degree of skill for proper splicing and terminating. A shift towards extruded dielectric cables began about 1975 in those metropolitan areas, but the majority of the distribution cables of the large cities remain paper insulated, lead-covered cables as the century ends.

Considerable research has been carried out by the utilities, technical organizations, and manufacturer's of cables to obtain improved paper and laminated PPP (polypropylene-paper-polypropylene, now used in transmission cables) tapes and insulating fluids able to withstand high, continuous operating temperatures, etc.

Impregnated paper insulation has excellent electrical properties, such as high dielectric strength, low dissipation factor, and dielectric loss. Because of these properties, the thickness of impregnated paper insulation was considerably less than for rubber or varnished cambric insulations for the same working voltages. Polyethylene and crosslinked polyethylene cables in the distribution classes are frequently made with the same wall thickness as today's impregnated paper cables

6. EXTRUDED DIELECTRIC POWER CABLES

The development of polyethylene in 1941 triggered a dramatic change in the insulation of cables for the transmission and distribution of electrical energy. There are two major types of extruded dielectric insulation in wide use today for medium voltage cables:

- (a) Crosslinked polyethylene or tree-retardant crosslinked polyethylene.

(b) Ethylene propylene rubber.

Thermoplastic polyethylene (PE), which was widely used through the 1970s, was introduced during World War II for high-frequency cable insulation. PE was furnished as 15 kV cable insulation by 1947. Large usage began with the advent of Underground Residential Distribution (URD) systems early in the 1960s.

7.0 URD SYSTEMS

The development of modern URD systems may be viewed as the result of drastically lowering first costs through technology.

Post-war URD systems were basically the same as the earlier systems except that there were two directions of feed (the loop system.) System voltages rose from 2400/4160 to 7620/13,200 volts. The pre-1950 systems were very expensive because they utilized such items as paper insulated cables, vaults, and submersible transformers. Those systems had an installed cost of \$1,000 to \$1,500 per lot. Expressed in terms of buying power at that time, you could buy a luxury car for the same price! Underground service was, therefore, limited to the most exclusive housing developments.

But for three developments in the 1960s, the underground distribution systems that exist today might not be in place. First, in 1958-59, a large midwestern utility inspired the development of the pad-mounted transformer; the vault was no longer necessary nor was the submersible transformer. Second, the polyethylene cable with its concentric neutral did not require cable splicers, and the cable could be directly buried. While possibly not as revolutionary, the load-break elbow (separable connector) allowed the transformer to be built with a lower, more pleasing appearance.

The booming American economy and the environmental concerns of the nation made underground power systems the watchword of the Great Society. In a decade, URD had changed from a luxury to a necessity. The goal for the utility engineer was to design a URD system at about the same cost as the equivalent overhead system. There was little or no concern about costs over the system's life because that PE cable was expected to last 100 years!

8.0 TROUBLE IN PARADISE

During the early part of the 1970s, isolated reports of early cable failures on extruded dielectric systems began to be documented in many parts of the world. "Treeing" was re-introduced to the cable engineer's vocabulary. This time it did not have the same meaning as with paper insulated cables. See Chapter 16 for additional information on treeing.

By 1976, reports from utilities [1-4] and results of EPRI research [1-5] confirmed the fact that thermoplastic polyethylene insulated cables were failing

in service at a rapidly increasing rate. Crosslinked polyethylene exhibited a much lower failure rate that was not escalating nearly as rapidly. Data from Europe confirmed the same facts [1-6].

The realization of the magnitude and significance of the problem led to a series of changes and improvements to the primary voltage cables:

- ☐ Research work was initiated to concentrate on solutions to the problem
- ☐ Utilities began replacing the poorest performing cables
- ☐ Suppliers of component materials improved their products
- ☐ Cable manufacturers improved their handling and processing techniques

9. MEDIUM VOLTAGE CABLE DEVELOPMENT [1-7]

In the mid 1960s, conventional polyethylene became the material of choice for the rapidly expanding URD systems in the United States. It was known to be superior to butyl rubber for moisture resistance, and could be readily extruded. It was used with tape shields, which achieved their semiconducting properties because of carbon black. By 1968, virtually all of the URD installations consisted of polyethylene-insulated medium voltage cables. The polyethylene was referred to as "high molecular weight" (HMWPE); this simply meant that the insulation used had a very high "average" molecular weight. The higher the molecular weight, the better the electrical properties. The highest molecular weight PE that could be readily extruded was adopted. Jacketed construction was seldom employed at that time.

Extruded thermoplastic shields were introduced between 1965 and 1975 leading both to easier processing and better reliability of the cable

Crosslinked polyethylene (XLPE) was first patented in 1959 for a filled compound and in 1963 for unfilled by Dr. Frank Precopio. It was not widely used because of the tremendous pressure to keep the cost of URD down near the cost of an overhead system. This higher cost was caused by the need for additives (crosslinking agents) and the cost of manufacturing based on the need for massive, continuous vulcanizing (CV) tubes. EPR (ethylene propylene rubber) was introduced at about the same time. The significantly higher initial cost of these cables slowed their acceptance for utility purposes until the 1980s.

The superior operating and allowable emergency temperatures of XLPE and EPR made them the choice for feeder cables in commercial and industrial

applications. These materials did not melt and flow as did the HMWPE material.

In order to facilitate removal for splicing and terminating, those early 1970-era XLPE cables were manufactured with thermoplastic insulation shields as had been used over the HMWPE cables. A reduction in ampacity was required until deformation resistant and then crosslinkable insulation shields became available during the later part of the 1970s.

A two-pass extrusion process was also used where the conductor shield and the insulation were extruded in one pass. The unfinished cable was taken up on a reel and then sent through another extruder to install the insulation shield layer. This resulted in possible contamination in a very critical zone. When crosslinked insulation shield materials became available, cables could be made in one pass utilizing "triple" extrusion of those three layers. "True triple" soon followed where all layers were extruded in a single head fed by three extruders.

In the mid 1970s, a grade of tree-retardant polyethylene (TR-HMWPE) was introduced. This had limited commercial application and never became a major factor in the market.

Around 1976 another option became available -- suppliers provided a grade of "deformation resistant" thermoplastic insulation shield material. This was an attempt to provide a material with "thermoset properties" and thus elevate the allowable temperature rating of the cable. This approach was abandoned when a true thermosetting shield material became available.

By 1976 the market consisted of approximately 45% XLPE, 30% HMWPE, 20% TR-HMWPE and 5% EPR.

In the late 1970's, a strippable thermosetting insulation shield material was introduced. This allowed the user to install a "high temperature" XLPE that could be spliced with less effort than the earlier, inconsistent materials.

Jackets became increasingly popular by 1980. Since 1972-73, there had been increasing recognition of the fact that water presence under voltage stress was causing premature loss of cable life due to "water treeing." Having a jacket reduced the amount of water penetration. This led to the understanding that water treeing could be "finessed" or delayed by utilizing a jacket. By 1980, 40 percent of the cables sold had a jacket.

EPR cables became more popular in the 1980s. A breakthrough had occurred in the mid-1970s with the introduction of a grade of EPR that could be extruded on the same type of equipment as XLPE insulation. The higher cost of EPR cables, as compared with XLPE, was a deterrent to early acceptance even with this new capability.

In 1981, another significant change took place: the introduction of "dry cure" cables. Until this time, the curing, or cross-linking, process was performed by

using high-pressure steam. Because water was a problem for long cable life, the ability to virtually eliminate water became imperative. It was eventually recognized that the "dry cure" process provided faster processing speeds as well as elimination of the steam process for XLPE production.

Another major turning point occurred in 1982 with the introduction of tree-resistant crosslinked polyethylene (TR-XLPE). This product, which has supplanted conventional XLPE in market volume today, shows superior water tree resistance as compared with conventional XLPE. HMWPE and TR-HMWPE were virtually off the market by 1983.

By 1984, the market was approximately 65 percent XLPE, 25 percent TR-XLPE and 10 percent EPR. Half the cable sold had a jacket by that time.

During the second half of the 1980s, a major change in the use of filled strands took place. Although the process had been known for about ten years, the control of the extruded "jelly-like" material was better understood by a large group of manufacturers. This material prevents water movement between the strands along the cable length and eliminates most of the conductor's air space, which can be a water reservoir.

In the late 1980s, another significant improvement in the materials used in these cables became available for smoother and cleaner conductor shields. Vast improvements in the materials and processing of extruded, medium voltage power cables in the 1980s has led to cables that can be expected to function for 30, 40, or perhaps even 60 years when all of the proper choices are utilized. In 1995, the market was approximately 45 percent TR-XLPE, 35 percent XLPE, and 20 percent EPR.

10. REFERENCES

[1-1] *Underground Systems Reference Book*, National Electric Light Association, Publication # 050, New York, New York, 1931.

[1-2] W. A. Thue, adapted from class notes for "Power Cable Engineering Clinic," University of Wisconsin -- Madison, 1997.

[1-3] *Underground Systems Reference Book*, Edison Electric Institute, Publication # 55-16, New York, New York, 1957.

[1-4] W. A. Thue, J. W. Bankoske, and R. R. Burghardt, "Operating Experience on Solid Dielectric Cable," *CIGRE Proceedings*, Report 21-11, Paris, 1980.

[1-5] Electric Power Research Institute EL-3154, "Estimation of Life

Expectancy of Polyethylene Insulated Cables," Project 1357-1, January 1984.

[1-6] UNIPEDE-DISCAB report.

[1-7] Bruce S. Bernstein, adapted from class notes for "Power Cables Engineering Clinic," University of Wisconsin -- Madison, 1997.